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Geothermal regime of the Williston Basin in North Dakota

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GEOTHERMAL REGIME OF THE WILLISTON BASIN IN NORTH DAKOTA

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This thesis, submitted by Faye Nicole Ricker in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Faye Nicole Ricker
May 01, 2015

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To my loving family:
A “thank you” wouldn’t begin to cover it.

ABSTRACT

Understanding the thermal regime of a large intracontinental basin such as the Williston Basin can be enhanced by analysis of the relationships among radiogenic heat production, surface heat flow, formation temperatures, and gravity and magnetic anomaly patterns. Digital processing of the spatial and causal relationships gives insight into the effect of basement heat production on the thermal state of the basement rocks and the overlying sedimentary successions. These relationships provide valuable insight on the radioactive heat contribution to heat flow, heat flow from the lower crust, composition of the upper crust, and the potential for geothermal power generation. The specific data used in this study include: radiogenic heat production values from well logs penetrating the Precambrian basement of the Williston basin in North Dakota, heat production values from gamma ray spectrometry on Precambrian basement core, tens of thousands of formation temperatures from the National Geothermal Data System borehole temperature data set, gravity and magnetic data (processed to generally characterize thickness and lithology of the radioactive layer), and stratigraphy and lithology.

Surface heat flow in the Williston basin cannot be predicted strictly by inputs from the mantle and from the radiogenic basement heat. The direct influence of basement heat production on heat flow through the sedimentary succession is visible for deeper units, but shallow and surface heat flow is perturbed by advection in younger aquifers. While potential for enhanced geothermal systems (EGS) and sedimentary enhanced

geothermal systems (SEGS) as well as co-produced and low temperature geothermal are ultimately controlled by temperature, understanding basement radioactivity can provide insight for delineating exploration areas.

CHAPTER I

INTRODUCTION

Describing the geothermal regime of an area requires an understanding of heat sources and the mechanisms by which heat is transported. In the stable continental interior, the two main sources of heat are heat flow from the mantle and radioactive heat production in the crystalline crust. For this study, the mechanisms of heat transport considered are convection by fluids moving in the basin, and conduction though the sedimentary strata.

In tectonically immature areas, heat flow at the crust-mantle boundary can be variable in magnitude and distribution. However, in stable continental interiors, contribution to heat flow from the lower crust and upper mantle is quite uniform over large regions (Roy, Blackwell, and Birch, 1968). The youngest tectonic events in the northern mid-continent were the 1.85 Ga Trans-Hudson orogeny and the 1.1 Ga Keweewanan Rift, thus heat flow at the crust-mantle boundary can be considered constant and uniform. Variability of radioactive heat production from basement rocks in the northern mid-continent is demonstrably a factor in surface heat flow. Low radioactivity in the mafic crust of the Keweenawan Rift is expressed as low heat flow, 40 to 50 mW/m^2, throughout Lake Superior and northern Minnesota. Heat flow west of the rift, where the crust consists of deeply eroded Proterozoic continental collision remnants, is on the order of 50 to 70 mW/m^2.

The geothermal regime of a sedimentary basin affects the accumulation, distribution, and utility of energy and mineral resources in that basin. Identification of geothermal resources, hydrocarbon type and maturity patterns, and types of mineral deposits is aided by understanding the magnitude and contribution of heat sources and heat transport mechanisms within the basin. Comparison of radiogenic heat production patterns with surface heat flow, formation temperatures, and gravity and magnetic data contributes to understanding the effect of basement heat production on the thermal state of the basement rocks and the overlying sedimentary succession. This analysis aids in identification of favorable areas for Enhanced Geothermal Systems (EGS) and sedimentary EGS as well as co-produced and low-temperature geothermal resources.

For this study, gamma ray values from well logs penetrating the Precambrian basement in the Williston basin of North Dakota were used to calculate radiogenic heat production. Heat production data were also obtained from gamma ray spectrometry performed on cores of the basement rocks and from previous literature. These data were compiled to establish patterns of spatial variability in radiogenic heat production for the region. Gravity and magnetics data were processed to generally characterize lithology of the radioactive layer and to identify any potential areas of focus for the study. Patterns in surface heat flow and heat flow through the sedimentary succession were obtained from conventional heat flow measurements and calculated from corrected bottom-hole temperatures (BHT). These data were contoured and mapped. The spatial and causal relationships between them were then explored to reveal the nature of the current thermal regime in the Williston Basin within North Dakota.

In similar studies of other sedimentary basins, convective heat transport is considered a far more influential factor in the distribution of surface heat flow variation than conductive heat transfer through the strata (Bachu and Burwash, 1994; Majorowicz et al., 1986; Jones and Majorowicz, 1987). The limited cross formational flow in bedrock aquifer systems, long tectonic quiescence, minimal hydraulic gradient, and wealth of oil and gas industry data makes the deeper North Dakota portion of the Williston Basin a great candidate for exploring the possibility of a different relationship between basement radioactivity and basin heat flow.

CHAPTER II

STUDY SETTING

Basin History

The Williston Basin is an ellipsoidal-shaped depression centered in western North Dakota and extending into parts of Montana, South Dakota, Manitoba, and Saskatchewan. It is flanked on the east by the Sioux Uplift, to the north by the Punnichy Arch and exposed Canadian Shield, and to the west by the Sweetgrass Arch. It is a structurally simple intracratonic sedimentary basin that contains an almost continuous stratigraphic record since the Middle Cambrian. The sedimentary secession has a maximum thickness of over 4km near the basin center in North Dakota, and its history is reflected in a suite of transgressive and regressive sequences indicative of a shallow marine environment (Porter, Price, and McCrossan, 1982).

The Williston Basin spans an international border, three domestic political boundaries in the United States, and two in Canada (Figure 1). The Western Canadian Sedimentary Basin underlies much of Western Canada including southwest Manitoba, southern Saskatchewan, almost all of Alberta, northeastern British Columbia, and the southwestern portion of the Northwest Territories. The geothermal regime of this area has been explored in detail by previous authors (Majorowicz, Jones, and Jessop, 1986; Bachu and Burwash, 1994; Jones and Majorowicz, 1987), and analysis of the Canadian portion of the Williston Basin is included in those works. The lack of data for the

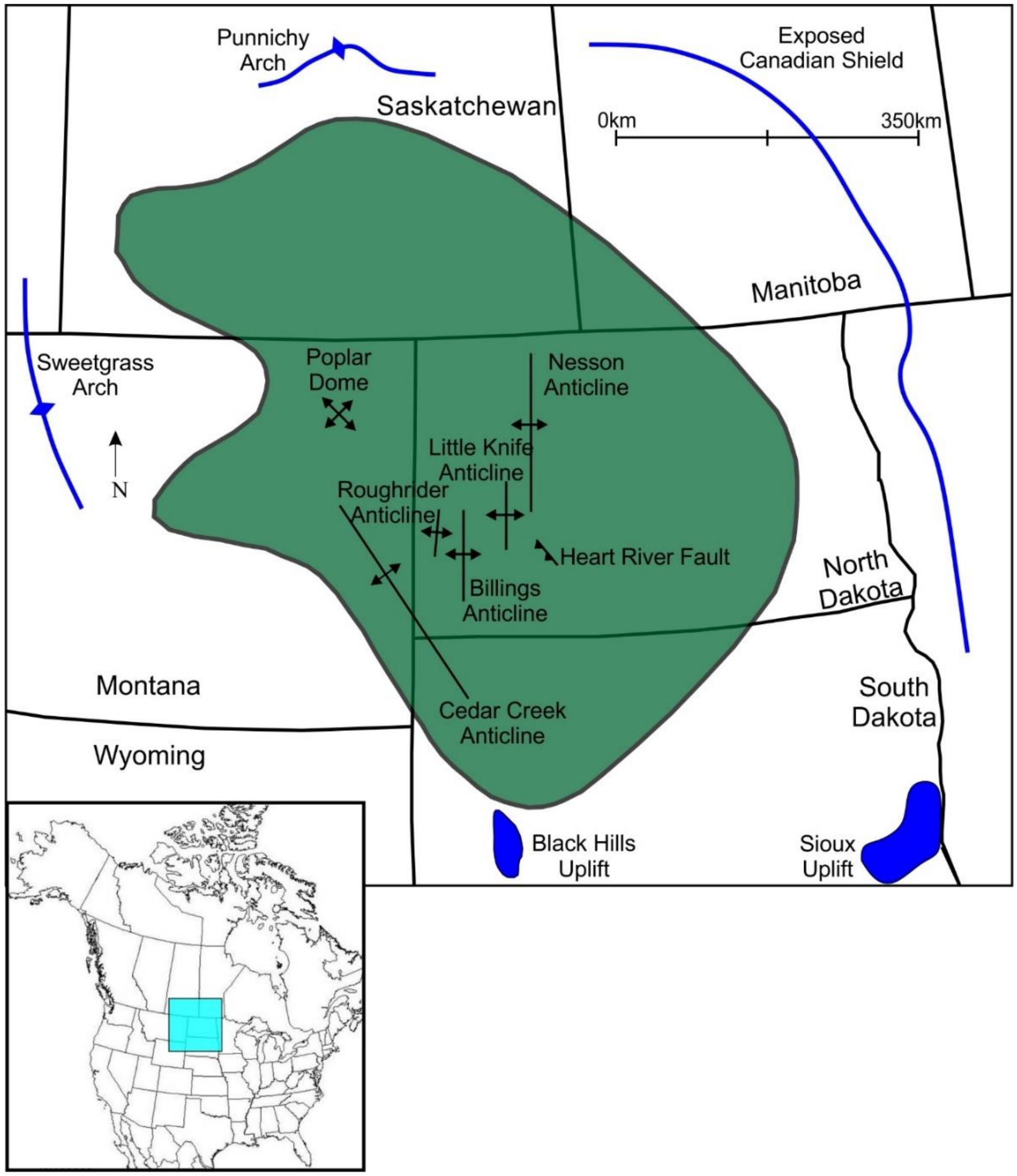


Figure 1. Location and outline of the Williston Basin showing major basement structures. (modified from Gerhard et al., 1982)

portions of the basin within Montana and South Dakota is prohibitive for conducting a basin wide analysis of geothermics. The North Dakota portion incorporates the deepest, most structurally significant, and most economically important elements of the basin. These attributes, combined with the higher density and better availability of relevant data, allows the narrowing of the study area to the North Dakota Portion of the basin.

Basement rock in North Dakota is composed of distinct Precambrian provinces; the Early Proterozoic Trans-Hudson orogenic belt consisting of mainly arc related rocks separates the Superior and Wyoming Archean cratons consisting of greenstone-granite and gneissic terranes (Figure 2). The Precambrian Trans-Hudson orogeny included northeast-trending fault and lineament zones which were reactivated at least three times during the Phanerozoic as far field responses to the Antler Orogeny (Devonian), and Cordilleran orogenic activity (Davies, 1998). This created new north–south and northwest–southeast oriented structures that were precursors to current structure in the basin such as the Nesson, Cedar Creek, Little Knife, Rough Rider, and Billings anticlines (Figure 1) (Burrett and Berry, 2000).

Sims et al. (1991) produced a map of basement terranes in the Trans-Hudson and the adjacent Archean provinces based on the work of Green, Cumming, and Cedarwell (1979), Green, Hajnal, and Weber (1985), and Green, Weber, and Hajnal (1985), who correlated lithostructural domains exposed in northern Saskatchewan and Manitoba with discrete magnetic regions delineated in southwestern Manitoba and southern Saskatchewan. The authors then extended these magnetic regions south into the United States. Klasner and King (1986) examined drill-hole, gravity, and magnetic data to delineate several basement terranes in the Dakotas; these closely resemble those suggested by Green et al. (1985).

Multiple mechanisms for the formation and subsidence of the basin have been explored. Authors have proposed an extensional setting, the result of faulting and rifting of the Trans-Hudson Orogenic belt following the suturing of the Archean Superior craton to the Archean Wyoming craton (Green et al., 1985), but the lack of an obvious rift basin

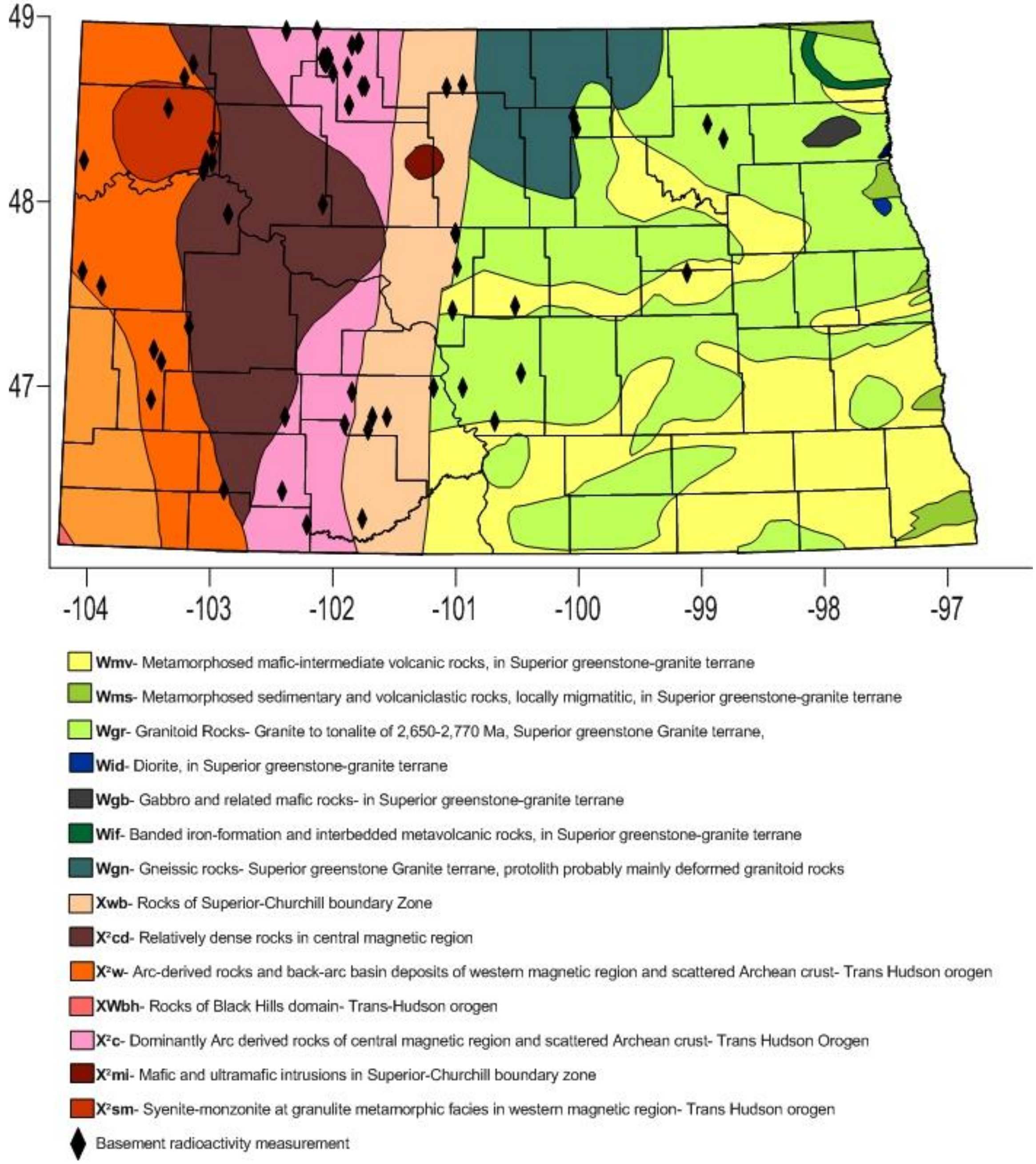


Figure 2. Map of basement units in North Dakota interpreted from gravity and magnetic data (modified from Sims et al. (1991).

or a sharply defined Moho beneath the Williston Basin makes it unlikely that crustal stretching and extensional tectonics drove the formation of the basin (Nelson et al., 1993). An alternative explanation proposed by Turcotte and Ahern (1977) and Ahern and

Mrkvicka (1984) attributes basin subsidence to the decay of a thermal anomaly in the lithosphere. The origin of the thermal anomaly is problematic, and calculated subsidence curves are incompatible with a thermal event (Fowler and Nisbet, 1984). Subsidence calculated from wireline logs shows relatively steady rates of a few meters per million years for most of the basin's history with abrupt episodes of rapid subsidence in the late Devonian (359 ma) and late Cretaceous (88 ma) (LeFever, 1988). The most likely mechanism for subsidence is reactivation of Trans-Hudson basement structures driven by sediment loading in the basin and far field tectonics (Green et al., 1985).

Hydrostratigraphy

The hydrologic system in the Williston Basin is established with the crystalline Precambrian basement as a lower boundary. The 4.5km of overlying Phanerozoic sedimentary strata can be divided into six hydrostratigraphic units consisting of aquifer and aquitard subunits based on the work of Downey (1986) and Bachu and Hitchon (1996) (Figure 3).

The sedimentary rocks of Cambrian and Ordovician age are grouped into the deepest major aquifer in the basin, composed principally of limestones and dolomites of the Red River Formation. The Interlake Formation (Silurian; silty, fine to medium crystalline dolomite and limestone) and Ashern Formation (Devonian; microcrystalline, anhydritic dolomite) overlie the Cambrian-Ordovician aquifer and act as a confining layer for this lower system (Downey, 1986; Bachu and Hitchon, 1996; Bluemle et al., 1986).

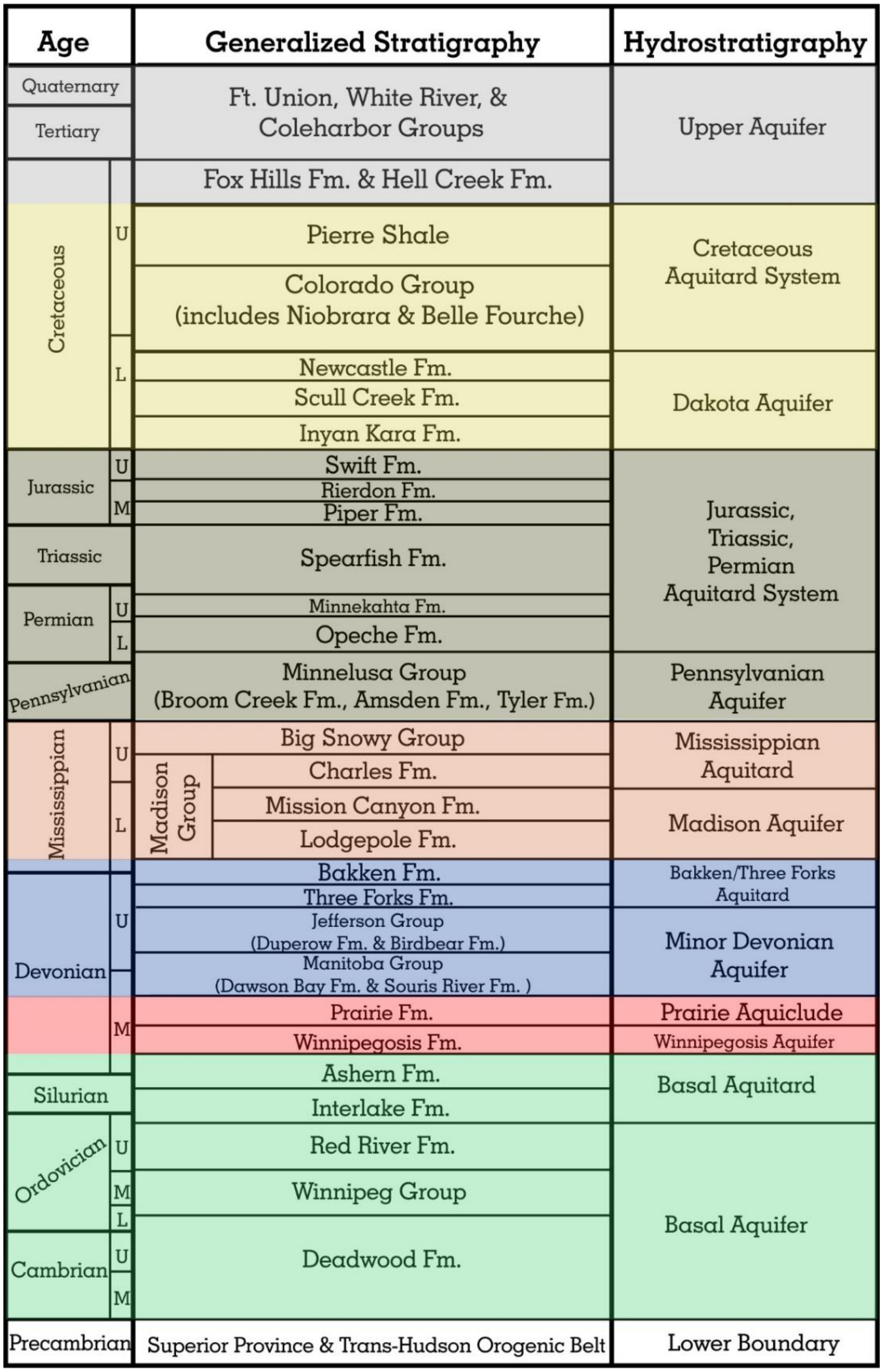


Figure 3. Hydrostratigraphic column of North Dakota portion of the Williston Basin with different colors representing different hydrostratigraphic units. (modified from Bachu and Hitchon, 1996)

Two minor sets of Devonian aquifer-aquitards conformably overlie the basal hydrostratigraphic unit. The first set is comprised of the reef and inter-reef limestones and dolomites of the Winnipegosis Formation and the confining evaporites of the Prairie Formation. The dissolution and absence of the Prairie Formation in places in the basin creates extensive conductivity between the two Devonian aquifers. The second aquifer-aquitard set is comprised of the porous, permeable, fossiliferous limestone of the Duperow and Birdbear Formations and the confining shales of the Three Forks and Bakken Formations (Downey, 1986; Bachu and Hitchon, 1996; Bluemle et al., 1986).

The second major aquifer is the Madison aquifer containing the Lodgepole and Mission Canyon Formations (Mississippian). These limestones and dolomites can be cherty to argillaceous and also contain minor anhydrite and gypsum beds. The Madison aquifer is confined by rocks of the Charles Formation and the Big Snowy Group. The confining Poplar interval of the Charles Formation contains halite, anhydrite, and mudstone deposits that severely limit vertical hydraulic conductivity. This very low vertical hydraulic conductivity isolates the Madison aquifer from other aquifers overlying it in the basin (Downey, 1986; Bachu and Hitchon, 1996; Bluemle et al., 1986).

The third major aquifer, the Pennsylvanian aquifer, is composed of sandstone and limestone of the Minnelusa Group (Broom Creek, Amsden, and Tyler Formations). Thick deposits of Permian, Triassic, and Jurassic shales and siltstones confine the Pennsylvanian aquifer. These rocks are minimally vertically permeable, and even further restrict the flow of water from the three lower Paleozoic aquifers to younger overlying aquifer systems (Downey, 1986; Bachu and Hitchon, 1996; Bluemle et al., 1986).

Lower Cretaceous sandstone and siltstone of the Inyan Kara, Skull Creek, and Newcastle formations forms the fourth major aquifer system. Known widely as the Dakota aquifer, it is the most developed bedrock aquifer in the northern Great Plains. This aquifer is capped by as much as a kilometer of shale and argillaceous limestone of the Pierre Shale, Belle Fourche shale, and Niobrara Formations (Downey, 1986; Bachu and Hitchon, 1996; Bluemle et al., 1986).

The upper boundary of the hydrologic system in the Williston Basin of North Dakota is the upper aquifer system. This aquifer system varies in composition from Upper Cretaceous sandstones to Quaternary glacial sediments and is unconfined (Downey, 1986).

Groundwater flow in the uppermost hydrostratigraphic units is local and mainly controlled by topography. In the deep bedrock aquifers, groundwater is confined and flow is regional (Thamke et al., 2014). The regional system is recharged mainly from streams draining the Bearpaw, Central Montana, and Black Hills uplifts and the Big Snowy and Big Horn mountains (Whitehead, 1996). The groundwater flows at very low rates from these recharge zones in the west toward the eastern and northeastern flanks of the shallow, bowl shaped basin. High-density brine is present in Paleozoic strata in the North Dakota portion of the basin, and freshwater is diverted around the brine (Figure 4) (Whitehead, 1996). The brine is moving slowly east-northeast with much lower velocities than the freshwater, allowing steady state conditions to prevail in the deep portions of the basin (Bachu and Hitchon, 1996).

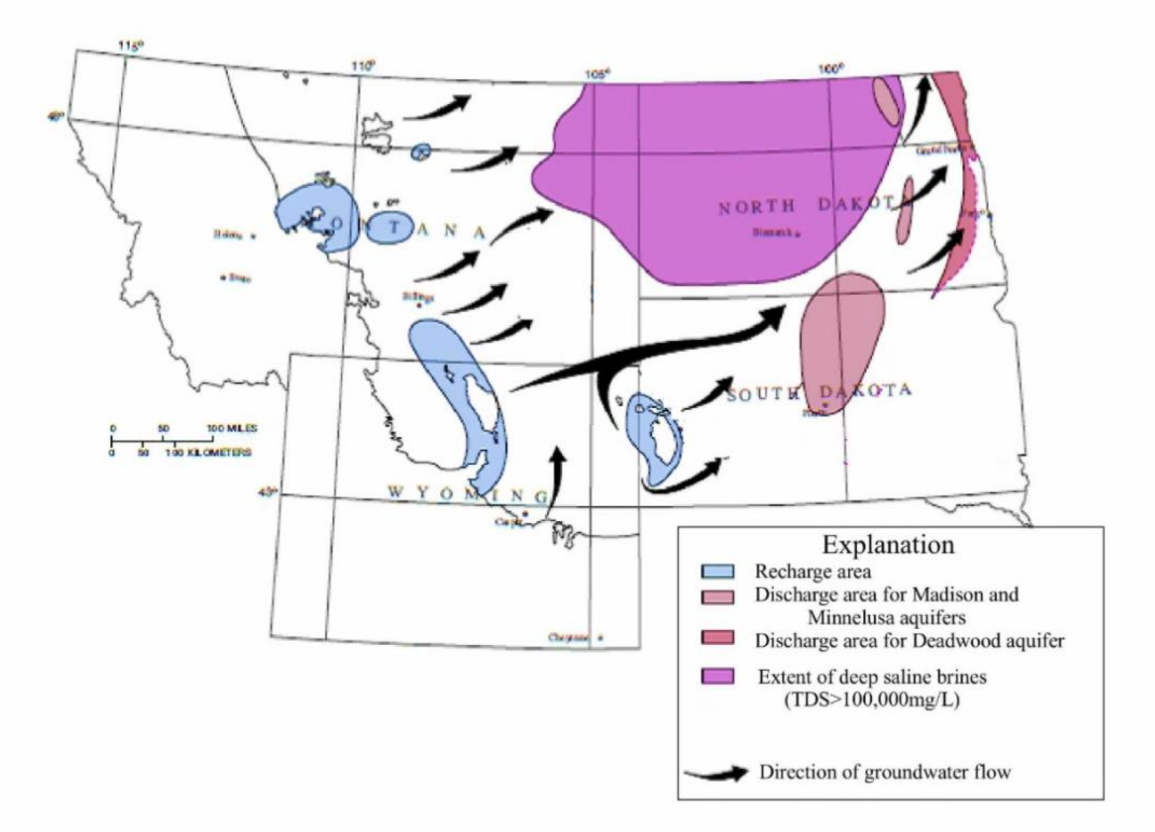


Figure 4. General direction of groundwater flow in regional Paleozoic aquifer systems. High density, slow moving brine shown in the deep North Dakota portion of the basin. (modified from Whitehead, 1996)

Gravity and Magnetics

Aeromagnetic and terrain corrected gravity data compiled and made publically available by the University of Texas, El Paso in cooperation with the USGS (Aldouri, 2002) were first examined in an attempt to delineate potential areas of focus for the study. The models prove unremarkable other than a small positive gravity and magnetic anomaly straddling Ward and McHenry counties. Cuttings from a well drilled into the basement there indicate a mafic intrusion. The basement terranes defined by Sims et al. (1991) (Figure 2) are discernable from the models; the east west trend of the alternating Superior Province granite greenstones are visible in the eastern portion of the models, and the north south trending Trans-Hudson orogenic terranes appear west of the boundary between the Precambrian provinces.

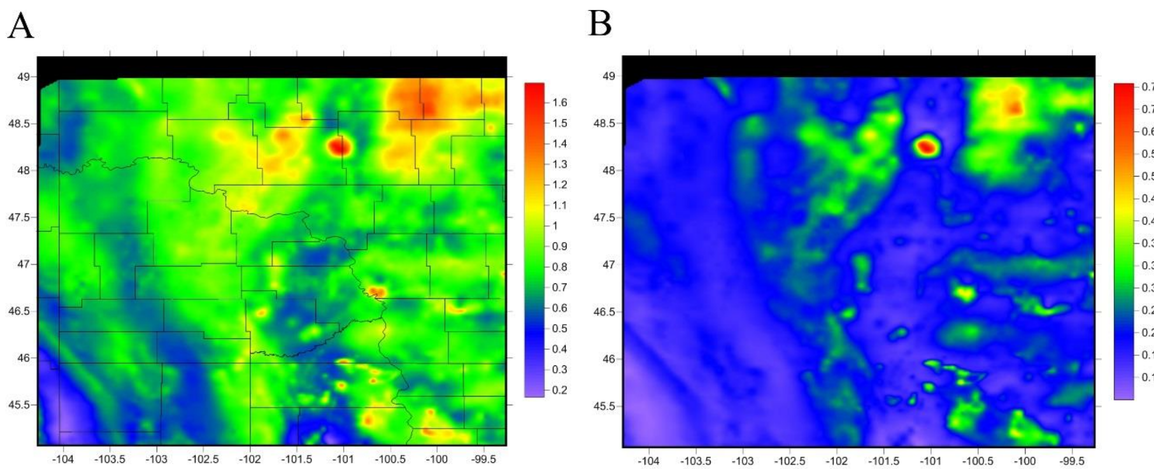


Figure 5. Gravity (A) and Magnetic (B) anomaly intensities. From the UTEP database for the western portion of North Dakota (Aldouri, 2002).

CHAPTER III

PREVIOUS WORKS

Gosnold (1999) speculated on general basin geothermics in the region based on 4 radiogenic heat production measurements by Scattolini (1977), conventional heat flow measurements, and limited BHT data. Local heat flow anomalies in the western portion of North Dakota were attributed to advective heat transport along structure in the basin. Majorowicz, Jones, and Ertman (1989) modeled hypothetical high basement radioactivity as one possible cause of the heat flow anomaly in the Williston Basin that coincides with an electrical conductivity anomaly observed from magnetotelluric studies (Jones, 1988; Jones and Savage, 1986). These authors suggest that the preferred cause for the anomalous heat flow and electrical conduction is mineralization and redistribution of radiogenic and electrical conductive elements in the crust during the Trans-Hudson Orogeny. This thesis confirms the existence of the levels of basement radioactivity modeled in the 1989 work and elucidates the role of advection in the geothermal regime.

Similar studies done in the nearby Western Canadian Sedimentary Basin, among other basins, have either been different in scope, tectonic setting, or data acquisition/processing methods. General conclusions drawn from these works limit the role of basement radioactivity in the overall geothermal regimes of the study areas; advective heat transport is considered a far more influential control (Bachu and Burwash, 1994; Majorowicz et al., 1986; Jones and Majorowicz, 1987).

Heat Generation and Heat Flow

For determining heat flow through strata where internal radiogenic heat generation is a factor, the following linear relationship has been established:

$$\boldsymbol{Q} = q + A_0 D \qquad \textbf{Equation 1.}$$

Where **Q** is surface heat flow, q is a constant component of heat flow from the mantle, A_0 is heat generation, and D is the thickness of the radiogenic heat producing layer (Lachenbruch, 1968; Roy, Blackwell, and Birch, 1968). Consistency in this linear relationship between heat generation and heat flow led to the definition of "heat flow provinces" by Roy, Blackwell, and Birch (1968). Heat flow provinces are regions or terranes with a common tectonothermal history within which heat flow from the lower crust and upper mantle is generally uniform and the thickness of the radiogenic heat producing layer is constant. The Northern Great Plains, and more specifically the Williston Basin, are included in the "Eastern US" heat flow province which is assigned a value of 7.5 km for the general thickness of the radiogenic heat producing layer.

Authors have proposed alternatives to the linear relationship between heat flow and heat production that include an exponential model of decreasing radioactivity with depth (Lachenbruch, 1970), a two layer model that includes an upper layer of variable thickness and heat generation underlain by a thicker, less variable layer (Drury, 1989), and a modeled fractal or power law type decrease in radioactivity with depth (Vedanti et al., 2011).

Where direct measurements of radioelements are not available, the linear relationship developed by Bücker and Rybach (1996),

$$A = 0.0158(GR - 0.8) \qquad \textbf{Equation 2.}$$

can be used to determine A (radiogenic heat production in $\mu W/m^3$) from standard Gamma Ray Log (*GR*) readings (in American Petroleum Institute (API) units) found in almost all modern well logs. This relationship was empirically determined and is valid over a wide range of lithologies (including granite, gneiss, carbonates, amphibolites, and basalts) and over the range of 0-350 API and 0.03-7$\mu W/m^3$, with an error lower than 10% (Bücker and Rybach, 1996; Beardsmore and Cull, 2001).

CHAPTER IV

METHODS

The approach taken in this investigation has 4 components: gravity and magnetic anomaly observations, determination of radiogenic heat production in basement rocks from well logs, estimates of heat flow from the mantle, and measurements of heat flow within the major hydrostratigraphic units in the basin.

Radiogenic Heat Production

The major heat-producing isotopes in the Earth's crust, ^{40}K, ^{238}U, ^{235}U, and ^{232}Th, release energy as they undergo radioactive decay. The gamma-ray spectra emitted from a rock can be analyzed to determine the proportion of each element, and in turn, the rate of heat production (in $\mu W/m^3$) for that sample.

Establishing the pattern of radiogenic heat production for basement rocks in the Williston Basin of North Dakota is made difficult by a deficiency of deep core samples for the area; only 10 cores penetrate more than one meter below the unconformable boundary between Phanerozoic sediments and the varied basement terranes. However, over 150 wells drilled in ND since the beginning of petroleum exploration activities in the Williston Basin have reached Precambrian basement rocks. Of these wells, 49 are recent enough and deep enough to have useful gamma ray logs.

Each of the 49 useable well logs was digitized using PETRA (IHS Inc., 2013), and the average Gamma Ray (API) value for the Precambrian rock at the base of the log was determined. Equation 2 yields an average heat production value for the Precambrian basement at each well. Using these data, gamma ray spectrometry on the limited core available, and some data from literature (Scattolini, 1978), two models of variation in radiogenic heat production were constructed in Surfer (Golden Software, 2014). The first model interpolated the A_0 values with no consideration of lithology. The second model constructed used the USGS map of basement rocks in North Dakota to assign an average A_0 value for each basement unit.

Heat Flow From the Mantle

This characterization of basement radioactivity creates an understanding of heat inputs for the basin. The "A_0D" term of Equation 1 is the heat flow component generated by the radioactive layer. If the heat flow from the lower crust and upper mantle is uniform and the thickness of the radioactive layer is constant, then differences in heat flow from the crystalline basement are determined solely by the variation in radioactivity of the upper crustal rocks. To calculate the contribution of heat flow from the mantle to overall heat flow, the contributions of radiogenic heat production from basement rocks and from the sedimentary succession were subtracted from total heat flow. The standard eastern US heat flow province thickness of 7.5km was used for the radioactive basement rocks. Heat production from the sediments was assumed to be $1.25\mu W/m^3$ due to the thick sequences of organic rich shales in the sedimentary succession (McKenna and Sharp, 1998; Beardsmore and Cull, 2001).

Receiver function data from the Earthscope Automated Receiver Survey (EARS) indicate that the crust is thicker in the western terranes of the Trans-Hudson orogenic belt underlying the Williston basin and thinner in the Superior and Wyoming Provinces. The

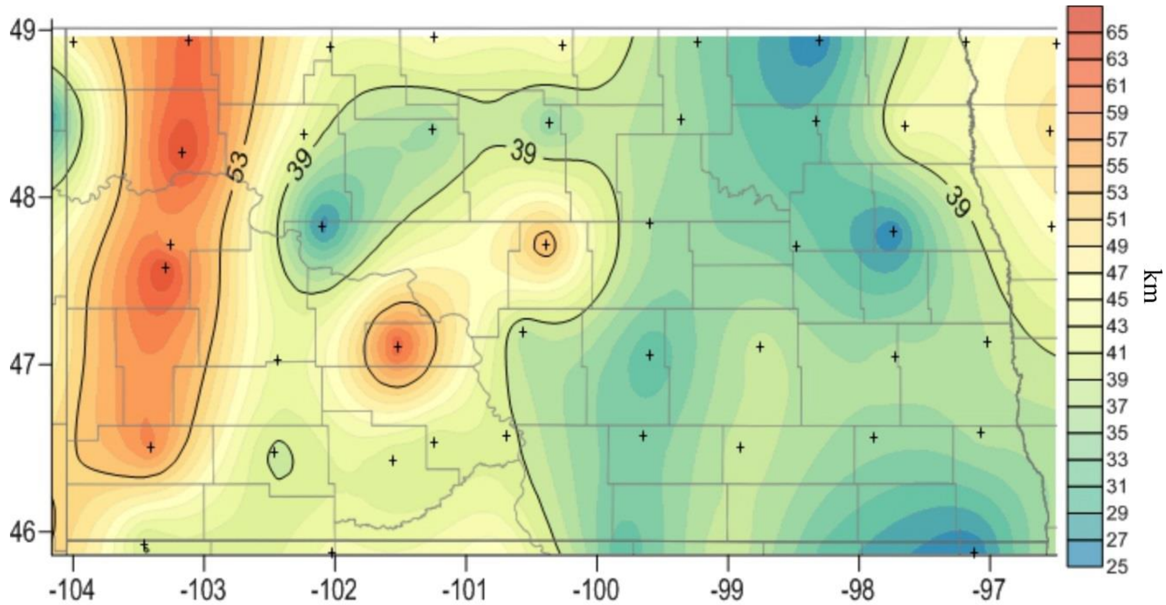


Figure 6. Crustal thickness in North Dakota from EARS data. (Crotwell and Owens, 2005; Trabant et al., 2012)

N-S trend of the thickness contours in the west parallels the trend of the arc terranes of the Trans-Hudson (Figure 5). If the volume of heat producing material is directly proportional to the thickness of the crust (Beardsmore and Cull, 2001) then the differences demonstrated by the EARS data need to be taken into account. Assuming a radioactive layer thickness of 15km (consistent with estimates by Gosnold (1999) for the thicker high heat producing terranes of the Trans Hudson, and the standard eastern US heat flow province thickness of 7.5km for the thinner Superior Province terranes, mantle heat flow components were recalculated.

Heat Flow in the Sedimentary Succession

If the heat flow from the lower crust and upper mantle remain constant, variability in upper crustal radioactivity (A_0) should generate the variable heat flow observed at the surface. However, surface heat flow shows complexity that is difficult to reconcile with such a simple conductive model of the crust. Topography, subsurface structure, thermal conductivity contrasts, transient sources and sinks, groundwater flow, and climactic changes can all affect observed surface heat flow. The difference in heat flow above and below an aquifer is the advective component of heat transport contributed by that aquifer (Gosnold, 1984), and calculating heat flow below the effects of fluid migration is essential for understanding the current thermal state and the thermal history of the basin (Beardsmore and Cull, 2001).

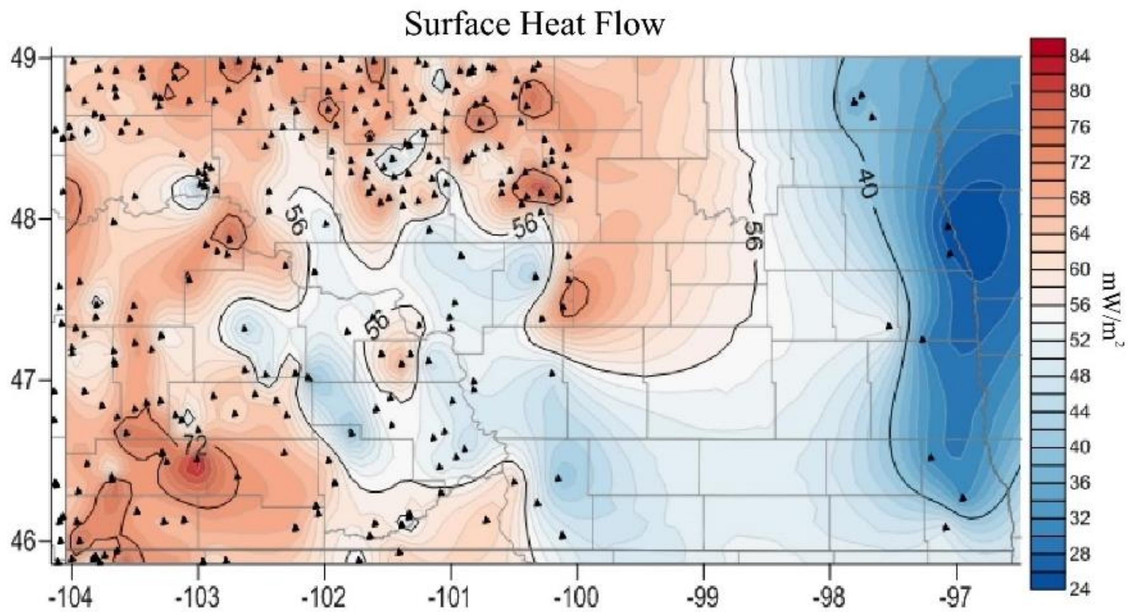


Figure 7. Surface heat flow in North Dakota. Data from the International Heat Flow Commission Database (IHFC, 2011). Triangles indicate measurement locations.

Bottom hole temperatures from the wealth of oil industry data in the state were compiled along with thermal conductivity and heat flow data gathered by the University of North Dakota Geothermal Laboratory to estimate the extent to which advective heat transport within each hydrostratigraphic unit contributes to the overall geothermal regime in the basin. Heat flow was calculated for the Red River, Bakken, Swift/Rierdon, Duperow, Deadwood, and Inyan Kara formations as well as the Madison Group. Each major hydrostratigraphic unit is represented at least once, with the exception of the upper, unconfined aquifer for which there is little to no thermal data. Calculating the thermal gradient rather than just observing formation temperatures eliminates the effect of increased temperature with burial depth. Using bottom hole temperatures, corrected for thermal disequilibrium (Crowell, Ochsner, and Gosnold, 2012), and mean annual surface temperature in the area, the thermal gradient from each of the formations to the surface was calculated.

$$Thermal\ Gradient = \frac{\Delta T}{\Delta z} = \frac{T_2(corrected\ BHT) - T_1(mean\ annual\ surface\ temp)}{Depth\ to\ Formation}$$

Equation 3.

Heat flow was then calculated using a harmonic mean thermal conductivity (λ_{HM}) based on formation thicknesses from the North Dakota Geological Survey and conductivities from the National Geothermal Data System compilation. Thermal conductivity is an inherent physical property of a medium that describes how easily that medium transmits heat.

$$Q = \lambda_{HM(above\ formation)} \left(\frac{\Delta T}{\Delta z}\right)$$ **Equation 4.**

CHAPTER IV

RESULTS AND DISCUSSION

Radiogenic Heat Production

Due to variation in radioactivity within the units, the model of basement radioactivity constructed using the USGS map of basement rocks in North Dakota to assign an average A_0 value for each basement unit yielded similar averages for most units and was not further considered. The model constructed by interpolation of the radioactivity values with no consideration of lithology is shown in Figure 4.

Radiogenic heat production in the basement rocks ranges from $0.04\mu W/m^3$ in the eastern portion of the basin underlain by the Archean Granite-Greenstone belts to $3.89\mu W/m^3$ in the arc/back-arc basin lithologies of the far western part of the state. Rather than coinciding with specific lithologies though, basement radioactivity trends higher parallel to the major structural features in the basin.

Heat Flow From the Mantle

As shown in Table 1, upper crustal contribution to total heat flow has a range of over $28 mW/m^2$ with a median effect of over $10 mW/m^2$. The variation in mantle heat flow calculated from these values is unrealistic and the magnitudes are up to $30 mW/m^2$ greater than that calculated by Majorowicz et al. (2014).

Table 1. Calculation of Mantle Heat Flow Component Assuming 7.5km Thick Radioactive Layer.

Thickness of radioactive layer: 7.5km	Heat production value ($\mu W/m^3$)	Upper crustal contribution to heat flow (mW/m^2)	Total Heat flow (mW/m^2)	Contribution from sediments (mW/m^2)	Heat flow from mantle (mW/m^2)
Maximum radiogenic heat production	3.890	29.2	83.5 (max)	Deepest portion(4.8km): 6	48.4
Minimum radiogenic heat production	0.0376	0.28	24.0 (min)	Shallowest portion(1.2km): 1.5	22.3
Median radiogenic heat production	1.505	11.3	54.0 (median)	Median(3km): 3.75	38.9

Using the variable model for thickness of heat generating crust proportional to crustal thickness results in mantle heat flow contributions that better fit the findings of Majorowicz et al. (2014) of 15 ± 5 mW/m^2 for the mantle derived component of heat flow in the Western Canadian Sedimentary Basin (Table 2). The new calculated values still show variation in mantle contribution to heat flow across the terranes, and this model is nonunique. Better understanding of the vertical and lateral distribution of radiogenic elements in the upper crust would refine the model.

Heat Flow in the Sedimentary Succession

The availability of BHT data is restricted by the areal extent of the formation and by the extent of oil companies' interest in exploration of the formation, so the coverage of the heat flow calculations is not uniform (as demonstrated by different areal coverages in Figure 9 A-G and in Appendix I). The density of data in the shallower two formations is much less than that of the deeper, more economically important formations.

Table 2. Calculation of Mantle Heat Flow Component With Proportionally Variability in Thickness of Radioactive Layer.

Proportional thicknesses for D	Heat production value ($\mu W/m^3$)	Thickness of radioactive layer, D	Upper crustal contribution to heat flow (mW/m^2)	Total Heat flow (mW/m^2)	Contribution from sediments (mW/m^2)	Heat flow from mantle (mW/m^2)
Maximum radiogenic heat production	3.89	15km	58.4	83.5 (max)	Deepest portion(4.8km): 6	19.2
Minimum radiogenic heat production	0.0376	7.5km	0.3	24.0 (min)	Shallowest portion(1.2km): 1.5	22.3
Median radiogenic heat production	1.505	15km	8.4	54.0 (median)	Median(3km): 3.75	27.7

Heat flow in the deepest formations (Deadwood, Red River, Duperow, Bakken, and Madison Group) mirrors the north/south trend of higher radioactivity detected in basement rocks. Little effect on heat flow by east-northeast flowing groundwater is detected in these formations. In the Swift/Rierdon and Inyan Kara, the heat flow pattern clearly reflects advection up-dip. The east-northeast direction of groundwater flow is observable via higher heat flow contours wrapping toward the basin margins and aquifer discharge zones as heat is transported in these younger, shallower hydrostratigraphic units. This phenomenon is documented in conventional heat flow measurements by Gosnold and Crowell (2014) as an up dip profile of increasing heat flow in the Pierre Shale near Minot, North Dakota on the northwestern flank of the Williston Basin. Were the current study expanded to include more of the shallower basin margins, where the dense slow-moving brines are not present in the strata, the effects of groundwater advection would likely be more pronounced, even in the deeper units.

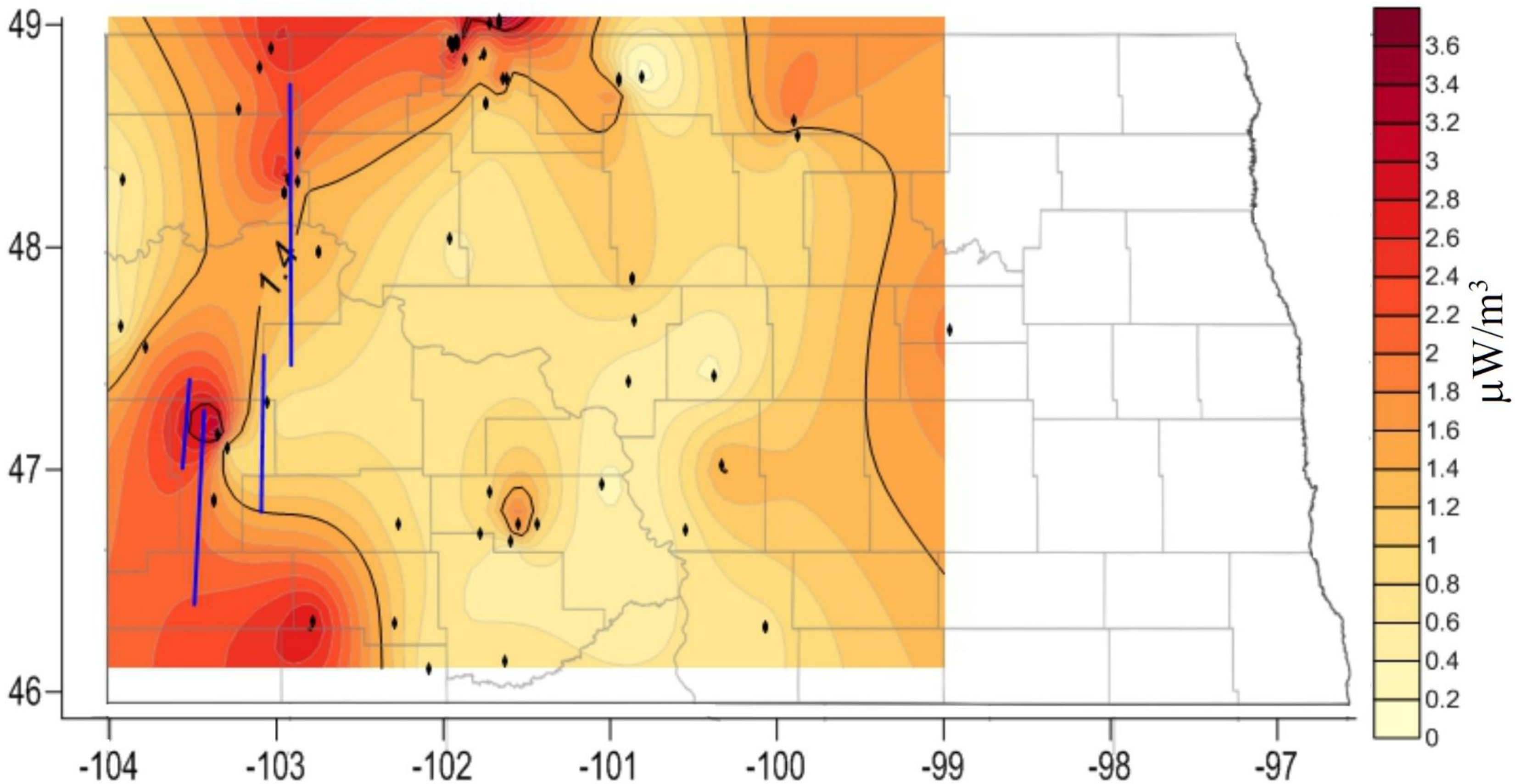
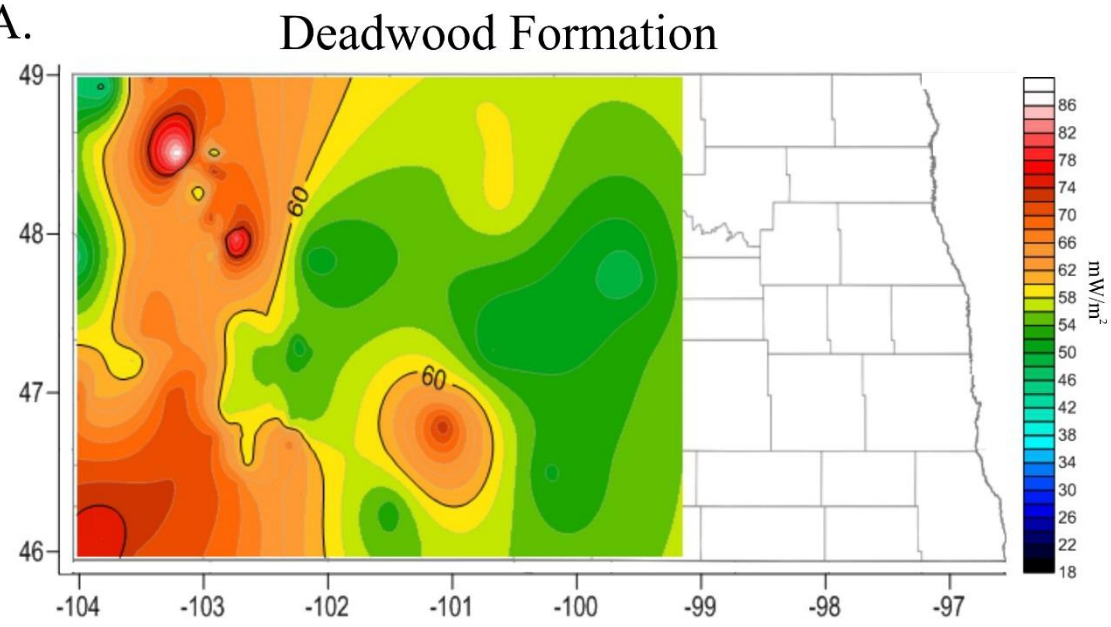
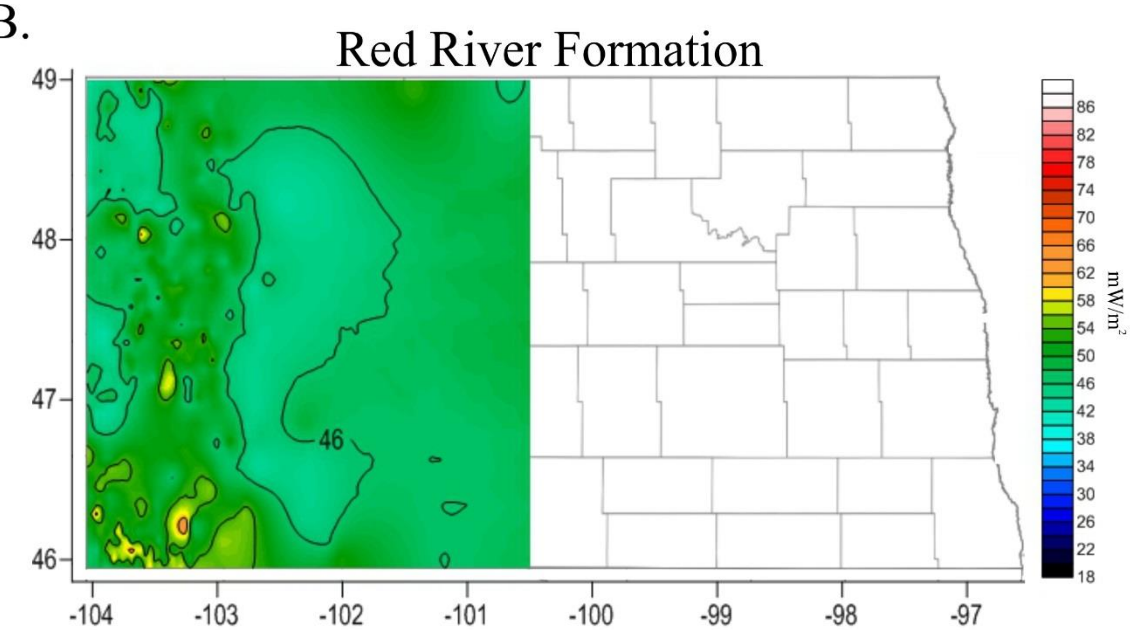


Figure 8. Radiogenic heat production from basement rocks underlying the Williston Basin of North Dakota. Blue lines represent major anticlinal structures, diamonds represent well and basement sample locations.

A.


Deadwood Formation
49
48
47
46
-104
-103
-102
-101
-100
-99
-98
-97
60
60
86
82
78
74
70
66
62
58
54
50
46
42
38
34
30
26
22
18
mW/m²

B.


Red River Formation
49
48
47
46
-104
-103
-102
-101
-100
-99
-98
-97
46
86
82
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74
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46
42
38
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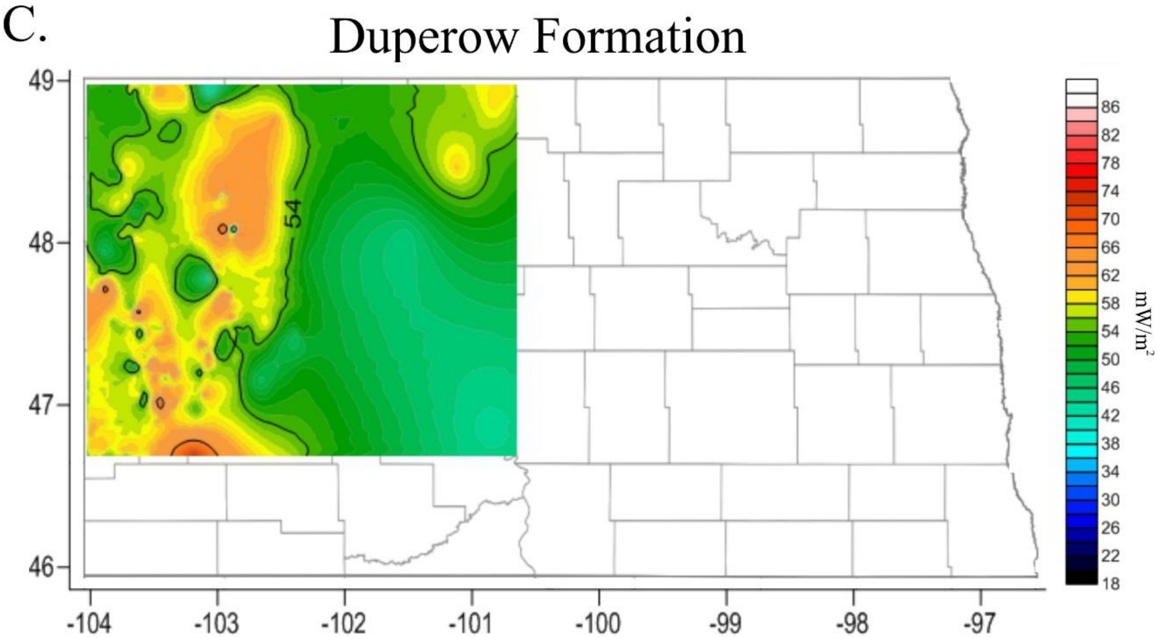
30
26
22
18
mW/m²

C.


Duperow Formation
54
49
48
47
46
-104
-103
-102
-101
-100
-99
-98
-97
86
82
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74
70
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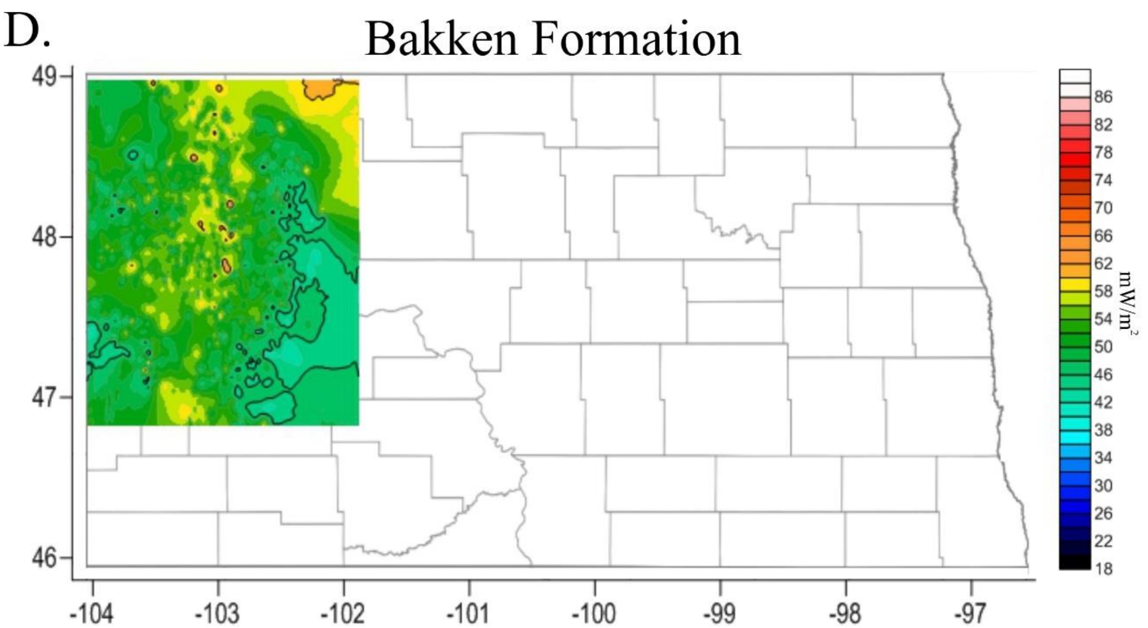
mW/m²

D.


Bakken Formation
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-104
-103
-102
-101
-100
-99
-98
-97
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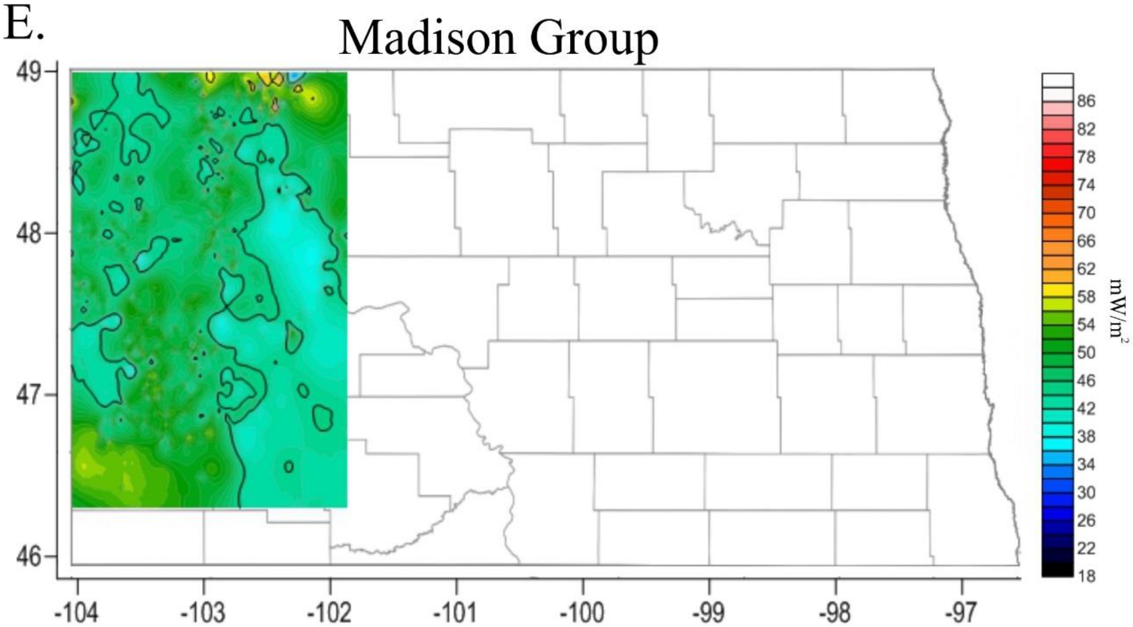
mW/m²

E.


Madison Group
49
48
47
46
-104
-103
-102
-101
-100
-99
-98
-97
86
82
78
74
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22
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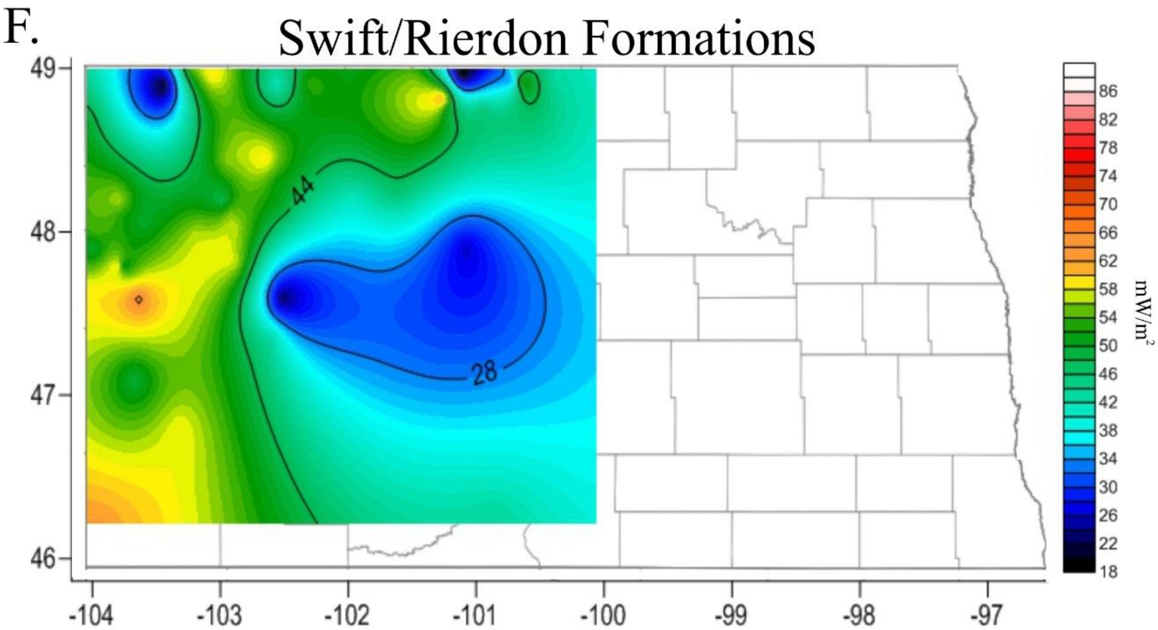
mW/m2

F.


Swift/Rierdon Formations
44
28
49
48
47
46
-104
-103
-102
-101
-100
-99
-98
-97
86
82
78
74
70
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54
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42
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30
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22
18
mW/m2

G.

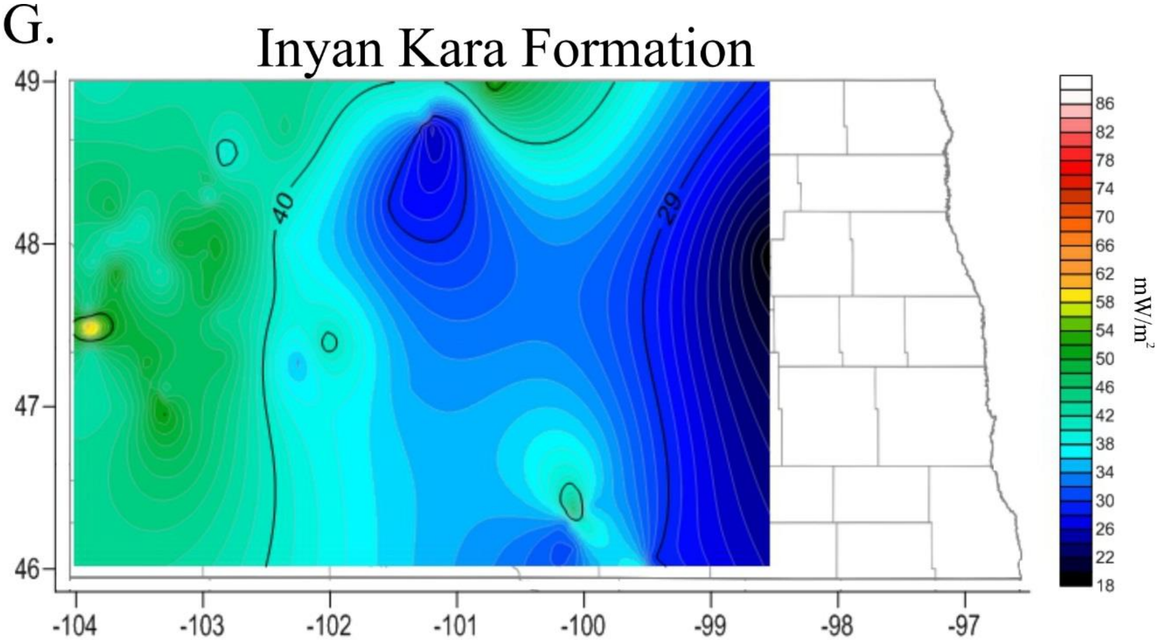


Figure 9. Heat flow through progressively younger formations in the Williston Basin. A.) Deadwood Formation. B.) Red River Formation. C.) Duperow Formation. D.) Bakken Formation. E.) Madison Group. F.) Swift and Rierdon Formations. G.) Inyan Kara Formation. Data derived from corrected BHT data and thermal conductivity measurements.

Basement Structure and Uranium Mineralization

Majorowicz (1989) and Gosnold (1999) suggested that high heat flow could be caused either by high heat generation in the Precambrian basement or high heat conduction related to saline brine in motion along basin structures. Due to the concurrence discovered in this study of higher basement radioactivity, higher heat flow though the sedimentary succession, and basement rooted structures in the western portion of North Dakota, distinguishing the contribution of each heat transport mechanism to the geothermal regime in the basin is very difficult. Likely, the mechanisms complement each other; basement rooted structures provide a conduit for convection of hydrothermal fluids along their general north-south trend, which parallels the trends in heat production in the crystalline basement. This allows the orientation of the higher heat flow pattern in the basin to be maintained.

Without denser and more abundant core sampling, a source for the higher radioactivity along the north-south trend in the basin remains hypothetical. The basement rock units which contain the highest levels of radiogenic heat production are varied in composition; limited drilling has intersected arc and back arc basin derived gneiss, granite, mafic granulite, charnockite, syenite and basalt (Sims et al., 1991). Average heat productions for these different lithologies span orders of magnitude (Beardsmore and Cull, 2001), making it unlikely that rock type is a control on the high radiogenic heat signal observed. Noting the coincidence of the higher radioactive heat production with the trend of basement structures, one possible source of the elevated radioactivity levels are syn- and post-orogenic hydrothermal fault fluid deposits of uranium.

Studies from the Beaverlodge area of northern Saskatchewan have concluded that far-field fault reactivation of basement rooted structure during the Kenoran (2.4 Ga), Thelon (1.85 Ga), and Trans-Hudson Orogens was a primary structural control for widespread uranium mineralization in fault mylonites, breccias and veins. (Bergeron, 2001) Each tectonic event is associated with a complex history of deformation and metamorphism, alteration, and a period of uranium mineralization. These basement-hosted deposits are formed when oxidized uranium-bearing brines (carrying leached uranium from shallow basement rocks or from overlying sediments) flow down fault controlled pathways deeper into the basement where they encounter reduced minerals or fluids and the uranium deposited (Cui, Yang, and Samson, 2010).

An investigation (closer in spatial and geologic context to the Williston Basin in North Dakota) of uranium and thorium deposits in the Western Canadian Sedimentary Basin found that the Proterozoic sedimentary cover, infaulted or infolded into the crystalline basement, was not a major source of high uranium values in the study area. The study concluded that hydration of Precambrian basement rocks, associated with fluid circulation, prevailed during the development of the shear zones in the basement and played a key role in the alteration and ore-forming processes (Burwash, 1979).

Structurally controlled mobilization of fluids along basement wrench faults in the terranes of the Trans-Hudson Orogen underlying the Williston Basin could have initialized hydrothermal alteration and uranium mineralization. The development and subsequent reactivations of these faults during basin subsidence could have a twofold effect on the geothermal regime in the basin; not only do the basement rooted faults provide a conductive conduit through the sedimentary layers, but their initial formation and subsequent reactivations acted as structural control on concentrated mineralization of uranium.

Concerning Paleo-heat Flow

Clues about the thermal history of the Williston basin can certainly be derived from the current geothermal regime; radioactive elements decay at a calculable rate, and the timing of basement fault reactivations that might control deposition of these elements is well constrained by basin subsidence curves. However, paleo-groundwater flow, paleo-water depth, sediment compaction, erosional episodes, paleoclimate, and changes in mantle heat flow over time are more difficult to parameterize. Characterizing paleo-heat flow through the sedimentary succession is important for understand patterns in hydrocarbon type and maturity, but has few implications for current geothermal energy resources and is therefore not considered in this study.

Play-fairway Analysis

A recent funding focus in the geothermal research community has been play-fairway analysis of geothermal resources. An approach used regularly in the oil and gas industry, play fairway analysis identifies areas where elements potentially favorable to resource development overlap. Elements considered by the oil and gas industry might be a probable caprock or the presence nearby of a hydrocarbon source. The elements favorable to possible geothermal resource development might be high formation temperatures, close proximity to power transmission infrastructure, or high surface heat flow. If play fairway analysis is undertaken for the Williston Basin or other basins with similar structural, thermal, and hydrologic characteristics, patterns of basement radioactivity should be an essential consideration. In these basins, deep sedimentary thermal resources are unlikely to resemble surface heat flow, but if data are available for heat production in the underlying crystalline rocks, it will provide an excellent first order investigative tool.

CHAPTER VII

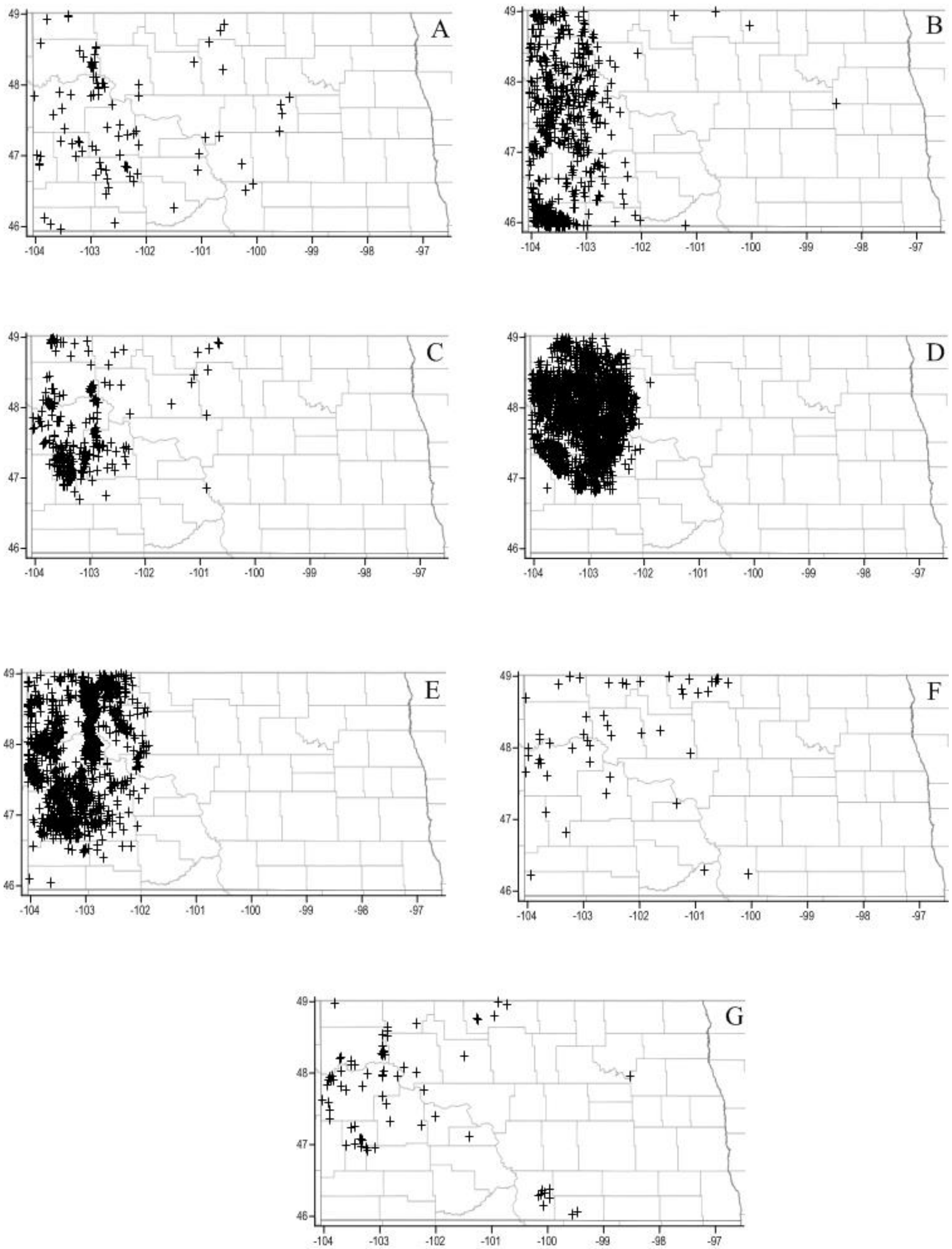
CONCLUSION

The relative structural simplicity, limited cross formational flow and deep slow-moving brines in bedrock aquifer systems, long tectonic quiescence, and density of oil and gas industry data in the Williston Basin make it a unique study area for geothermics.

Radiogenic heat production from basement rocks in North Dakota is variable across and within units of the Precambrian rock, but shows a general higher trend that parallels some of the major structures in the basin. Careful inspection of the heat flow across specific sedimentary units reveals that radiogenic heat production from basement rocks and convection along sub-vertical basement rooted faults are the primary control on the deeper geothermics in the basin, but heat flow through shallow formations and surface heat flow is perturbed by groundwater advection in bedrock aquifers. This conclusion has implications for the methods of exploration of deep thermal resources in the basin. Surface heat flow is not an accurate predictor of heat flow in units below the disruptive signal of groundwater movement. These deeper, hotter resources are better modeled using the heat flow signal from the mantle and basement.

Future investigations into the geothermal regime of the Williston Basin should incorporate all new thermal data available including careful consideration and correction of BHTs, refining estimates of heat production from the sedimentary succession, analyzing any new basement samples or GR logs, and expanding analysis into the shallower portions of the basin in Montana and South Dakota (hinging on data availability).

APPENDIX



Distribution of wells with bottom hole temperatures used to determine heat flow at surfaces within the sedimentary succession A.) Deadwood Formation. B.) Red River Formation. C.) Duperow Formation. D.) Bakken Formation. E.) Madison Group. F.) Swift and Rierdon Formations. G.) Inyan Kara Formation.

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